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Han-Li Liu

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Atmospheric Research
3090 Center Green Drive,
Boulder, CO 80305

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4555 Overlook Ave. SW
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Publications, WACCM-X Model and its simulation results are publicly available.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In this work, we have achieved the project goal by (1) enhancing, testing, and delivering WACCM-X model to the overall project PI, Dr. F. Sassi and the NRL team; (2) enabling coupling of WACCM-X with the NAVDAS system, and with the NRL SAMI3 ionosphere and plasmasphere model; (3) collaborating on scientific studies of planetary waves and their impact in the lower thermosphere. A final report detailing these achievements is attached.

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Final Report: Impacts of Stratospheric dynamics on atmospheric behavior from the ground to space under solar minimum and solar maximum conditions (Contract No.: N00173-12-1-G010 NRL)

Project Summary: Dynamical response to solar radiative forcing is a crucial and poorly understood mechanisms. We propose to study the impacts of large dynamical events on both the troposphere and the thermosphere during different phases of the solar cycle. The scientific objectives of this proposed research are intimately connected with the integrated response of the whole atmosphere to solar variability. In particular we compute and analyze the solar-induced variations of the following: (1) the penetration into the thermosphere of wave dynamics associated with disturbed events in the stratosphere; and (2) the influence of the stratosphere on the tropospheric climate during different phases of the solar cycle. In addition, a third objective of our research plan is to provide a fiducial simulation of the whole atmosphere up to 500 km which will allow the community to investigate in detail the sources and mechanisms that generate seasonal variations in the thermosphere (annual and semiannual variations). For this purpose, we will exercise the newly developed and updated extension of the Whole Atmosphere Community Climate Model (WACCM-X) to 500km which provides the most comprehensive ground-to-thermosphere modeling capacity to date. To specify the stratospheric dynamical events as realistically as possible, the meteorology of the atmosphere below 90 km is constrained to the observed state using data assimilation products from the Naval Research Laboratory Atmospheric Variational Data Assimilation System (NAVDAS) or from the NASA Modern Era Retrospect Analysis for Research and Applications (MERRA). The quality of the model simulations (thus constrained) in the thermosphere will be assessed by comparing to the globally averaged mass density dataset developed at Naval Research Laboratory that covers the last 40 years and, where available, to composition, temperature and density profiles from the Global Ultraviolet Imager (GUVI) onboard of the NASA/TIMED satellite.

Definition of NCAR's Role: NCAR PI H.-L. Liu will help the PI (F. Sassi) interfacing the DAS products with the WACCM-X for the different time periods and provide initial conditions for solar minimum and solar maximum. He will assist the rest of the team members in the validation of the thermospheric products.

Accomplishments

A. WACCM-X Development:

The NCAR Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X) has been further developed, tested, and delivered to the project PI, Dr. F. Sassi and the NRL team. Main developments include: (i) Developed and tested WACCM-X with specified dynamics capability (SD-WACCM-X). With this capability, the WACCM-X meteorological fields from the troposphere up to the mesopause can be specified by NAVDAS forecast results. This model setup (SD-WACCM-X/NAVDAS) has been used for case studies (discussed later). (ii) Developed a module to couple WACCM-X with an ionosphere/plasmasphere model. This module

allows the exchange of neutral fields from WACCM-X with ionospheric drifts, plasma density and electric conductivities from an ionosphere/plasmasphere model. Dr. F. Sassi and the NRL team has been able to couple WACCM-X with the NRL SAMI3 model. (iii) Implementation of time-dependent electron and ion temperature solver. In the middle and upper thermosphere, the thermal electron heating of the neutral atmosphere is the dominant heating source and thus important for thermosphere energetics. With this new implementation, the thermosphere temperature is higher and in better agreement with observations. (iv) Implementation of hydrogen escape flux at the model top boundary. A constant hydrogen flux was used in previous version of WACCM-X, which is partly responsible for the disagreement of various hydrogen species (e.g. H2O and CH4) with climatology. Recently an empirical formulation has been adapted from TIME-GCM and implemented in WACCM-X. This has resulted in better representation of these species by WACCM-X. Apart from these development efforts, we have also maintained and regularly update the WACCM-X to the latest CESM and CAM version.

B. Scientific Studies

B.1 The Lower thermosphere during northern hemisphere winter of 2009

Numerical simulations were conducted using the SD-WACCM-X, constrained below 90 km by a combination of NASA's MERRA and the U.S. Navy's NOGAPS-ALPHA assimilation products. The period examined is January and February 2009, when a large stratospheric warming occurred on 24 January 2009, with anomalous circulation persisting for several weeks after the event. In this study, we focus on the dynamical response of the lower thermosphere up to 200 km. We find evidence of migrating and non-migrating tides, Rossby and Rossby-gravity modes, and Kelvin waves, whose amplitudes appear to be modulated at the times leading and following the stratospheric warming. While the Rossby, Rossby-gravity and Kelvin modes are rapidly dissipated in the lower thermosphere (above 110 km), the tides maintain substantial amplitude throughout the thermosphere, but their vertical structure becomes external above about 120-150 km. Most waves identified in the simulations decrease in amplitude in the thermosphere, indicating remote forcing from below and strong dissipation by molecular diffusion at high altitudes; however, the amplitude of the migrating DW1 tide increases in the thermosphere suggesting *in situ* forcing. We show that the amplitude of the tides (such as the DW1) changes as the background wind alters the vorticity in the tropics, which broadens or narrows the tropical waveguide. Our results also suggest that fast Rossby normal modes (periods $\leq$ 10 days) are excited by instability of the zonal mean wind distribution following the stratospheric warming.

Sassi, F., H.-L. Liu, J. Ma, and R. R. Garcia, The lower thermosphere during the northern hemisphere winter of 2009: A modeling study using high-altitude data assimilation products in WACCM-X, J. Geophys. Res., 118, doi:10.1002/jgrd.50632, 2013.

B.2 Westward traveling planetary wave events in the lower thermosphere during solar minimum conditions

The focus of this study is to describe how various dynamical conditions of boreal winter affect the dynamical behavior of the lower thermosphere (90-150 km). SD-

WACCM-X simulations were made whose dynamies is constrained by atmospheric specifications during recent and historical solar minimum conditions. The model simulations are carried out during solar minimum conditions and the results shown here discuss the period January 1 - March 30 for five years (1995, 1996, 2008, 2009, and 2010). These years were selected because they include boreal winters without stratospheric warming (1995 and 1996), with modest or normal stratospheric warming (2008, 2010), and with a large and persistent stratospheric warming (2009). The ultimate goal of this study is to encapsulate the statistically significant dynamical behavior due to westward propagating, planetary-scale waves (wavenumber 1 and wavenumber 2) in the lower thermosphere that are associated with different stratospheric conditions. To this end we show that the westward zonal acceleration above about 80 km is by and large described by traveling waves with periods between 2 and 10 days. We show that the momentum carried by these waves is unlikely to affect directly the momentum budget of the extra-tropical lower thermosphere, where instead gravity-wave drag figures prominently. However, at the times leading to and following large stratospheric disturbances, we show prominent meridional propagation of wave activity from the mid-latitudes toward the tropics. In combination with strong eastward meridional wind shear, our results provide further evidence that such equatorward propagation of momentum in the lower thermosphere might influence the amplitude of equatorially trapped tides.

Sassi, F., and H.-L. Liu, Westward traveling planetary wave events in the lower thermosphere during solar minimum conditions simulated by SD-WACCM-X, J. Atmos. Solar Terr. Phys., 119,11-26, doi: 10.1016/j.jastp.2014.06.009, 2014.

B.3 *Traveling planetary-scale waves in the lower thermosphere: Effects on Neutral Density and Composition During Solar Minimum Conditions*

The effects of breaking and dissipation of traveling, planetary scale Rossby waves (TPWs) in the lower thermosphere are investigated with respect to the mixing of neutral constituents, using WACCM-X whose meteorology below 92 km is constrained by atmospheric specifications obtained from operational weather forecast/data assimilation system. The simulations are carried out for the January-February months during the last solar minimum, 2008, 2009 and 2010. The Fourier spectra show that the amplitude of TPWs with periods between 3 and 10 days at mid-latitudes in the lower thermosphere are statistically significant in some years; the amplitude and phase of the band-pass filtered behavior is consistent with the behavior of the 5-day wave, the fundamental Rossby normal mode. A wavelet analysis using the S-transform (ST) shows that large variations with periods between 3 and 10 days can occur in relatively narrow temporal windows (20–30 days) during boreal winter; by exploiting the correspondence between the time-averaged ST and the Fourier spectrum, we determine the time dependent statistical significance of those amplitudes.The momentum flux entering the lower thermosphere during the times of TPW amplification is shown to be also large. Interestingly, these amplifications of the TPWs and the associated momentum flux in the thermosphere are not always associated with disturbed stratospheric events, such as stratospheric sudden warming (SSW). The zonal acceleration due to TPW events is largest at mid-latitudes in the lower thermosphere below 120 km, as expected, and in some winters it shows substantial magnitudes in the tropics during TPW events; the sub-tropical zonal

accelerations are consistent with Rossby wave encountering a surf zone at low latitudes, resulting in Rossby wave breaking and dissipation. The zonal acceleration is shown to be associated with a meridional diffusion, which is largest in the lower thermosphere where the zonal acceleration is also large. The ultimate effect on neutral density and composition is a meridional, down-gradient mixing; although this horizontal diffusion is largest below 110 km, the effects on the composition are amplified with increasing altitude, due to the diffusive separation of the thermosphere.

Sassi, F., H.-L. Liu, and J. T. Emmert, Traveling planetary-scale waves in the lower thermosphere: Effects on Neutral Density and Composition During Solar Minimum Conditions, J. Geophys. Res., under review.

B.4. *The neutral dynamics during the 2009 sudden stratosphere warming simulated by different whole atmosphere models*

This study compares simulations of the 2009 sudden stratospheric warming (SSW) from four different whole atmosphere models. The models included in the comparison are the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy, Hamburg Model of the Neutral and Ionized Atmosphere, Whole Atmosphere Model, and WACCM-X. The comparison focuses on the zonal mean, planetary wave, and tidal variability in the middle and upper atmosphere during the 2009 SSW. The model simulations are constrained in the lower atmosphere, and the simulated zonal mean and planetary wave variability is thus similar up to ~1 hPa (50 km). With the exception of WACCM-X, which is constrained up to 0.002 hPa (92 km) by NOGAPS-ALPHA, the models are unconstrained at higher altitudes leading to considerable divergence among the model simulations in the mesosphere and thermosphere. We attribute the differences at higher altitudes to be primarily due to different gravity wave drag parameterizations. In the mesosphere and lower thermosphere, we find both similarities and differences among the model simulated migrating and nonmigrating tides. The migrating diurnal tide ($DW1$) is similar in all of the model simulations. The model simulations reveal similar temporal evolution of the amplitude and phase of the migrating semidiurnal tide ($SW2$); however, the absolute $SW2$ amplitudes are significantly different. Through comparison of the zonal mean, planetary wave, and tidal variability during the 2009 SSW, the results of the present study provide insight into aspects of the middle and upper atmosphere variability that are considered to be robust features, as well as aspects that should be considered with significant uncertainty.

Pedatella, N. M., T. Fuller-Rowell, H. Wang, H. Jin, Y. Miyoshi, H. Fujiwara, H. Shinagawa, H.-L. Liu, F. Sassi, H. Schmidt, V. Matthias, and L. Goncharenko, The neutral dynamics during the 2009 sudden stratosphere warming simulated by different whole atmosphere models, J. Geophys. Res., 119, 1306-1324, doi:10.1002/2013JA019421, 2014.

B.5. Ionosphere variability during the 2009 SSW: Influence of the lunar semidiurnal tide and mechanisms producing electron density variability

WACCM-X, constrained by NOGAPS-ALPHA, and TIME-GCM are used to investigate ionosphere variability during the 2009 sudden stratosphere warming (SSW). The simulations reveal notable enhancements in both the migrating semidiurnal solar (*SW*2) and lunar (M_2) tides during the SSW. The *SW*2 and M_2 amplitudes reach $\sim$50 m s^{-1} and $\sim$40 m s^{-1}, respectively, in zonal wind at *E* region altitudes. The dramatic increase in the M_2 at these altitudes influences the dynamo generation of electric fields, and the importance of the M_2 on the ionosphere variability during the 2009 SSW is demonstrated by comparing simulations with and without the M_2. TIME-GCM simulations that incorporate the M_2 are found to be in good agreement with Jicamarca Incoherent Scatter Radar vertical plasma drifts and Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) observations of the maximum *F* region electron density. The agreement with observations is worse if the M_2 is not included in the simulation, demonstrating that the lunar tide is an important contributor to the ionosphere variability during the 2009 SSW. We additionally investigate sources of the *F* region electron density variability during the SSW. The primary driver of the electron density variability is changes in electric fields. Changes in meridional neutral winds and thermosphere composition are found to also contribute to the electron density variability during the 2009 SSW. The electron density variability for the 2009 SSW is therefore not solely due to variability in electric fields as previously thought.

Pedatella, N. M., H.-L. Liu, F. Sassi, J. Lei, J. L. Chau, and X. Zhang, Ionosphere variability during the 2009 SSW: Influence of the lunar semidiurnal tide and mechanisms producing electron density variability, J. Geophys. Res., 119, doi:10.1002/2014JA019849, 2014.

B.6. Day-to-day variation of the equatorial electrojet during quiet periods

It has been known for a long time that the equatorial electrojet varies from day to day even when solar and geomagnetic activities are very low. The quiet time day-to-day variation is considered to be due to irregular variability of the neutral wind, but little is known about how variable winds drive the electrojet variability. We employ a numerical model introduced by Liu et al. (2013), which takes into account weather changes in the lower atmosphere and thus can reproduce ionospheric variability due to forcing from below. The simulation is run for May and June 2009. Constant solar and magnetospheric energy inputs are used so that day-to-day changes will arise only from lower atmospheric forcing. The simulated electrojet current shows day-to-day variability of ±25%, which produces day-to-day variations in ground level geomagnetic perturbations near the magnetic equator. The current system associated with the day-to-day variation of the equatorial electrojet is traced based on a covariance analysis. The current pattern reveals return flow at both sides of the electrojet, in agreement with those inferred from ground-based magnetometer data in previous studies. The day-to-day variation in the electrojet current is compared with those in the neutral wind at various altitudes, latitudes, and longitudes. It is found that the electrojet variability is dominated by the zonal wind at 100–120 km altitudes near the magnetic equator. These results suggest that the response

of the zonal polarization electric field to variable zonal winds is the main source of the day-to-day variation of the equatorial electrojet during quiet periods.

Yamazaki, Y., A. D. Richmond, A. Maute, H.-L. Liu, N. M. Pedatella and F. Sassi, On the day-to-day variation of the equatorial electrojet during quiet periods, J. Geophys. Res., 119, doi:10.1002/2014JA020243, 2014.